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MANAGEMENT OF TECHNOGENIC SAFETY BASED ON A RISK-ORIENTED APPROACH[1]

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Abstract. This paper proposes a managerial decision algorithm based on the developed risk assessment methodology with multidimensional statistical analysis. The methodology allows calculating an acceptable risk level, which can be used in regulatory documents. The decision algorithm is integrated into the information system of territorial risk and safety management. The industrial agglomerations of Siberia are chosen as the object of study, and their main types of technogenic hazards are analyzed. The complex risk is assessed using statistical data on man-made dangerous events, emergencies, material damage, and fatal outcomes from the official database (the Emercom of Russia). According to risk factor analysis, the main technogenic load in territorial units is due to fire and explosive events. The inverse problem is solved, showing the need to reduce the main risk factors for achieving an acceptable level. Minimizing the complex technogenic territorial risk is a management problem with two criteria: the minimum number of fatal outcomes and the minimum amount of damage. Within the complex risk assessment approach, the problem is solved by proposing preventive measures to improve territorial safety.

Keywords: socio-natural-technogenic system, territorial risk, management.

INTRODUCTION

The sustainable development of territories is based on balancing economic growth, safety, social responsibility, and environmental conditions. To implement effective management, it is advisable to analyze territorial units using the concept of a socio-natural-technogenic (S-N-T) system [1–5]. Such a system represents a unified complex of interrelated elements of the social and ecological technosphere with different groups of risks [2, 6, 7]. In the presence of hazardous natural processes and the growing number of complex man-made systems, the conditions for developing territorial units are related to realizing, identifying, and minimizing risks[2]. The requirements for risk identification, assessment, and management were enshrined in federal laws [8–10], and the need to counteract the factors that may, directly or indirectly, deteriorate national interests was reflected in the decrees of the President of the Russian Federation [11, 12].

Intelligent systems are created for comprehensive management tasks at different levels and in different areas. Such systems integrate, store, and process significant flows of information. In recent years, many software complexes and systems have been developed in Russia and abroad to process monitoring information [13–28]. However, such systems have a highly

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[2] Risk is a quantitative measure of hazard that simultaneously characterizes the occurrence of unfavorable phenomena, events, or processes in a complex S-N-T system and the severity of their consequences [29].

specialized orientation. Under the rapidly growing volumes and flows of information, assessing the state of S-N-T systems is a complex scientific and applied problem. It can be solved by developing information-analytical systems with risk assessment.

The greatest hazard[3] for human life and health is posed by man-made accidents and disasters. They characterize the technosphere, a component of the S-N-T system. Violations of technological, managerial, and organizational processes in industrial and administrative activities cause a wide range of technogenic dangerous events: transport accidents, explosions and large fires, collapses of supporting structures, accidents involving the release of hazardous chemical and radiation substances, destruction of main pipelines, and accidents in life support systems (power grids, housing and communal services systems, and heating networks).

1. ANALYSIS AND PROBLEM STATEMENT

In this paper, we analyze and assess the technogenic load in industrial agglomerations of the Siberian Federal District (SFD): Krasnoyarsk, Novosibirsk, and Omsk. The greatest hazard in these territories is all types of fires, large motor vehicle accidents, and accidents in life support systems.

Urbanization processes and the growing industry in cities negatively affect environmental and social safety. They cause several problems requiring the constant attention of federal and municipal authorities:

– the high concentration of potential hazards in limited areas (nuclear cycle enterprises, the military-industrial complex, pipelines, oil and gas storage facilities, hydroelectric power plants, chemical and metallurgical production, etc.);

– the increased probability of emergencies due to high wear and tear of the main production assets;

– the factors associated with a low safety culture.

To date, a major problem is to improve the sustainable development and operation of territorial units through effective management. To solve this problem, we propose using an information system of territorial risk and safety management (further called the information system, IS) [1]. It is intended to identify territorial risks and minimize them to scientifically reasonable acceptable levels.[4] This system allows integrating the accumulated experience in the network monitoring of the environment and technosphere, analysis technologies for large volumes of information, safety and risk theory, territorial management mechanisms, and methods of forecasting socio-economic development.

2. A METHODOLOGY FOR ASSESSING COMPLEX TECHNOGENIC TERRITORIAL RISK

The complex technogenic territorial risk and the limit state of the technosphere objects within the S-N-T system are assessed using hierarchical cluster analysis [5, 31]. We divide the SFD territories into cluster groups and select a reference group for comparison and determination of the acceptable risk level.

Hierarchical cluster analysis allows grouping objects with similar characteristics. At the first step, each object (territorial unit) in a sample is considered a separate cluster. The clusters are formed sequentially by uniting the closest objects. The objects are classified by their similarity depending on the metric distance between them. Each object is described by k features and represented as a point in the k-dimensional space, and its similarity with other objects is defined through a corresponding measure. If the similarity matrix has the initial dimensions $m \times m$, the clustering process will be completed in $(m – 1)$ steps; eventually, all objects will be combined into one cluster.

The risk assessment methodology based on cluster analysis includes eight stages as follows.

Stage 1 (formulation of the problem). It is required to analyze the technogenic safety of SFD cities with over 70 thousand residents according to the municipal unit classification [32].

Stage 2. Quantitative indicators are selected for the analysis (statistical data from the official database of the computerized information and management system for emergency prevention and control for the period 1999–2020).

Stage 3. The initial indicators are represented as the quantitative values of vulnerability[5]. They have a probabilistic nature and vary in the range [0, 1]:

$$\vartheta = \{p_a; p_f; p_e\}, \quad (1)$$

[3] *Hazard* is an objectively existing possibility of an adverse effect on an object or process, which may cause any damage or harm deteriorating its state and assigning undesirable dynamics or parameters (in terms of character, pace, form, etc.) [30].

[4] *The acceptable risk level* is a scientifically grounded quantitative risk value that can be accepted by a person, society, and the state during a given period [29].

[5] *Vulnerability* is a system parameter characterizing the possibility of any damage to a given system [33]; for territorial units, vulnerability is defined as the degree of possible losses due to the adverse effect of some process or phenomenon of a given level [30].

where ϑ denotes the vulnerability of a territory, and p_a, p_f, and p_e are the probabilities of a dangerous event, a fatal outcome in a dangerous event, and an emergency, respectively. Based on vulnerability values, the cities are divided into cluster groups.

Stage 4 concerns determining the distance between objects in a conditional multidimensional space. The Euclidean distance and its square, the Manhattan distance (between city blocks), and the Chebyshev distance are commonly used to measure the distance between two points (characterizing the proximity or similarity of objects) in the coordinate axes *x* and *y*. Different measures are applied to justify the correctness of clustering. The uniform distribution of clusters obtained by different measures validates the chosen classification method.

Stage 5. A clustering method is chosen to calculate the distances between clusters. Ward's method is the best clustering method for objects with a "blurred" structure and fuzzy condensation. This method yields small and compact clusters as follows. In the first step, each cluster consists of one object. Next, the two closest clusters are combined. For these clusters, the average values of each feature are determined, and the sum of squared deviations is calculated:

$$V_k = \sum_{i=1}^{n_k}\sum_{j=1}^{p}\left(x_{ij} - \overline{x}_{jk}\right)^2,$$

where the subscripts *k*, *i*, and *j* correspond to the cluster, object, and feature, respectively; *p* is the number of features characterizing each object; n_k is the number of objects in cluster *k*; $\overline{x}_{jk}$ is the average value of feature *j* in cluster *k*; finally, x_{ij} is the value of feature *j* for object *i*.

The clusters with the smallest increase in the total sum of distances are combined into one group.

Stage 6 is to determine the number of hierarchical tree clusters. In this paper, we determine the number of clusters using k-means: for a specified number of clusters (2, 3, 4, etc.), the division of the hierarchical tree is checked sequentially.

Stage 7 deals with a quantitative assessment of technogenic risks for each cluster group. The complex technogenic territorial risk R_c (further called the risk value) is assessed by the formula

$$R_c = \sum_{i=1}^{n} N_i\left(Q_i\right)P_i\left(Q_i\right)U_i\left(N_i,\, Q_i\right),$$

$$R_c \le \left[R\right], \qquad (2)$$

where n denotes the number of hazard types; $N_i\left(Q_i\right)$ is the probability of fatal outcomes (the number of deaths divided by population size) due to the realization of different hazard types; $P_i\left(Q_i\right)$ is the probability of a dangerous event on a given territory per unit time; $U_i\left(N_i,\, Q_i\right)$ is the material damage from a source of hazards and fatal outcomes, in RUB; finally, $\left[R\right]$ is an acceptable risk level, in RUB per year. The assessment (2) covers the entire list of hazards in a given territory and the amount of damage due to the corresponding dangerous events.

Stage 8. A reference group of clusters with the lowest risk value is selected. The acceptable risk level is calculated as a confidence interval over the reference group [5, 31]. For large Siberian cities with over 70 thousand residents, the calculated acceptable risk level corresponds to the interval [0, 2.1].

Additional data analysis is required when obtaining a high risk value. Here, the best approach is to solve inverse problems (determine the dominant factors affecting the risk value and identify the parameters to be managed). In optimal conditions, within the concept of non-zero risk, the total value of the complex technogenic territorial risk over various types of man-made events should not exceed the acceptable value:

$$R_c = \sum_{i=1}^{n} R_{c_i} = R_{c_1} + R_{c_2} \ldots + R_{c_n}$$

$$R_{c_1} \ll \left[R\right];\ R_{c_2} \ll \left[R\right];\ldots R_{c_n} \ll \left[R\right], \qquad (3)$$

where R_{c_i} is the complex technogenic territorial risk due to the realization of given-type events.

Upon determining the dominant factors, it is necessary to minimize the risk value through appropriate measures. Risk management methods are directed actions to reduce hazards and their consequences. Minimizing the risk value (2) is a management problem with two criteria: the minimum number of fatal outcomes $F\left(N_i\right)$ and the minimum amount of damage $F\left(U_i\right)$:

$$\begin{cases} F_1\left(N_i\right) \to \min, \\ F_2\left(U_i\right) \to \min. \end{cases}$$

Imposing an upper bound constraint *C* on one criterion, we obtain two optimization problems:

$$\begin{cases} F_1\left(N_i\right) \to \min, \\ F_2\left(U_i\right) \le C_1, \end{cases} \quad \begin{cases} F_2\left(U_i\right) \to \min, \\ F_1\left(N_i\right) \le C_2. \end{cases} \qquad (4)$$

The rapid response to an emergency to reduce material losses directly depends on the number of fire and rescue units. On the other hand, the availability of a sufficient number of medical facilities can reduce the number of fatal outcomes. To elaborate protection improvement measures, an important problem is to assess quantitatively the provision $Z_{(\tau)}$ of the necessary number of medical facilities and fire and rescue units in the territorial entity:

$$Z_{(\tau)} = \left(\frac{N_{\text{fire}}^{\text{fact}} + N_{\text{med}}^{\text{fact}}}{N_{\text{fire}}^{\text{norm}} + N_{\text{med}}^{\text{norm}}} \right) \cdot 100 \geq 100\% , \qquad (5)$$

where $N_{\text{fire}}^{\text{fact}}$ and $N_{\text{fire}}^{\text{norm}}$ are the factual and normative numbers of fire and rescue units in a given territory, and $N_{\text{med}}^{\text{fact}}$ and $N_{\text{med}}^{\text{norm}}$ are the factual and normative numbers of medical facilities in a given territory.

A territory is protected if $Z_{(\tau)} \geq 100\%$, i.e., the factual numbers of medical facilities and fire and rescue units are not smaller than their normative counterparts. The normative number of fire and rescue units is calculated using the normative number of personnel of fire protection units involved in rescue work and the standard staffing structure:

$$N_{\text{fire}}^{\text{norm}} = \frac{N_{\text{res}}}{N_{\text{fire}} N_{\text{staff}}} , \qquad (6)$$

where N_{res} is the number of residents in a given territory; N_{fire} is the number of residents per one member of the fire and rescue unit; finally, N_{staff} is the typical number of rescuers in the unit.

The number N_{fire} is calculated as [34]

$$N_{\text{fire}} = 0.036757 \cdot P \left(0.036648 + 98.781 \cdot P^{-0.44823} \right)^2 , \ (7)$$

where P is the population density in the territory.

The normative number of medical facilities is determined according to the regulatory document of the Ministry of Health [35].

Thus, the clustering of territorial units by the technogenic danger indicators (1) together with the cluster assessments of risks (2) and (3) and protection (5)–(7) are used to analyze the technogenic safety of territorial units comprehensively within the risk-oriented approach [31].

3. SOFTWARE AND HARDWARE IMPLEMENTATION

Evaluating the complex technogenic territorial risk is a main function of the information system of territorial risk and safety management (the IS). Its general block diagram is based on Docker containers: in this container (module) management system, each separate module is placed as an independent component (program) on the computing server and has a dedicated access port and a particular set of libraries. Thus, an application or website with all its environment and dependencies is packed into a container, which can be easily managed: transferred to another server, scaled, or updated. The graphical interface of the IS is based on ReactJS + Redux libraries. The system uses a complex crisis database with the PostgreSQL database management system [36].

In this paper, we propose a managerial decision algorithm embedded in the information system of territorial risk and safety management; see Fig. 1 and [1, 31].

The IS receives statistical data characterizing the S-N-T system (territory). It includes two subsystems:

- The information subsystem "Monitoring." This subsystem collects and systematizes information flows of the monitoring systems with subsequent processing, analysis, and storage of the data.
- The information subsystem "Risk Analysis." This subsystem has three blocks: the crisis databases of the S-N-T system, a cartographic database of a geographic information system, and a block with basic risk analysis models and computational technologies. This subsystem quantitatively assesses the risk (identification, classification, assessment, and determination of an acceptable level).

After the information passes through these subsystems, the data are processed to calculate the risk values within the methodological approach presented above.

An appropriate conclusion with territory management and planning measures is formed depending on the calculated risk value. If the risk value corresponds to an acceptable level, no additional measures to reduce the risk in the territory are required. If a high risk level is obtained, additional data analysis is carried out to identify the dominant risk factor.

The resulting information is used to generate an intermediate product (a conclusion on necessary measures to minimize the risk value for a particular factor by improving the protection of objects, reducing man-made hazards, and increasing the stability of objects; see Table 1) and control the risk level.

The conclusion is sent to the decision-maker, who analyzes the information received and approves the measures under the available budget. This system yields regulatory documents (orders or decrees) with risk management methods. Note that preventive measures differ depending on the type of dangerous factors (man-made event) and budget constraints; see Table 2.

Territorial units are dynamic systems, and the calculated risk value will change over time. Thus, for effective management, the results should be annually corrected.

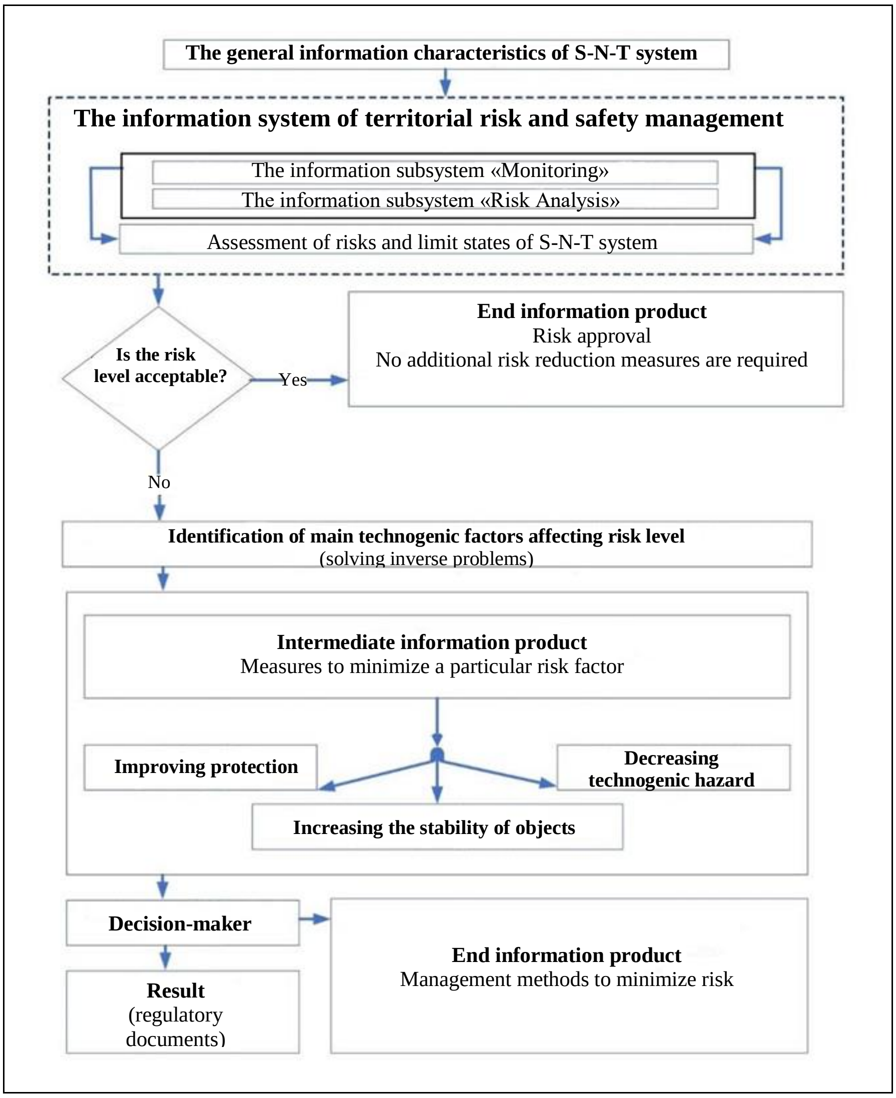

Fig. 1. The managerial decision algorithm within the risk-oriented approach.

Table 1

The main types of preventive measures to improve the technogenic safety of a territory

The goals of preventive measures	Technological solutions, preventive measures
Reducing the probability of dangerous events	- Repair and reconstruction of technosphere objects; - Construction of all types of facilities using new technologies with safety requirements; - Continuous monitoring of adverse processes; - Automation of processes (reducing the role of the human factor)
Increasing the stability of objects	- Zoning of territories adjacent to technosphere objects; - Development of healthcare and safety systems; - Engineering solutions to improve the stability of the urban environment; - Development of warning and alarm systems; - Property insurance; - Control, supervision, prevention, and education of residents
Increasing protection	- Creation and upgrading of emergency response units and services; - Creation, replenishment, and replacement of reserves in case of emergency; - Increase in financial reserves; - Improving interagency interaction, working with volunteers

Table 2

Measures to prevent or reduce the consequences of major dangerous man-made events

The type of dangerous event	Preventive measures		
	Reducing the probability of occurrence	Reducing the scale of emergencies	Actions without resource constraints
Accidents at potentially dangerous facilities	Increasing the «sensitivity» of industrial control systems to the identification of accidents and emergencies. Inspections by the Federal Service for Environmental, Technological and Nuclear Supervision (Rostekhnadzor)	Increasing the readiness of the facility units. Improving emergency response plans	Transition to alternative technologies. Reduction (complete rejection) of hazardous substances and materials
Man-made fires	Strengthening of fire supervision. Control of knowledge of fire safety rules	Installation of modern firefighting equipment. Improving the readiness of the emergency response units. Improving emergency response plans	Transition to alternative production and construction technologies
Domestic fires and fires at mass public facilities	Strengthening of fire supervision. Training of the population in fire safety rules	Increasing the number and status of firefighting units. Creating resources for firefighting	Transition to alternative construction technologies. Elimination of stove heating
Accidents of housing and communal services systems	Increasing the volume and quality of capital repairs	Increasing the readiness of units. Improving emergency response plans	Transition to alternative technologies and materials when replacing service lines
Motor vehicle accidents	Legislative regulation of safety issues	Training in first aid. Increasing the readiness of rescue units	Construction and reconstruction of roads in accordance with modern standards (four lanes, interchanges)

4. PRACTICAL RESULTS

The proposed methodology was used to analyze 31 territorial units of the SFD with over 70 thousand residents. As found, in Krasnoyarsk, Novosibirsk, and Omsk, the complex technogenic territorial risk value exceeds the maximum permissible level hundreds of times. Figure 2 shows the distribution of the complex technogenic territorial risk values for each type of dangerous events in these Siberian agglomerations.

The main technogenic load in urban units falls on various fire-explosive events and large motor vehicle accidents. The lowest risk value was obtained for such indicators as «Collapse of structures» and «Other» (aerial, rail, and river vehicle accidents, accidents at industrial facilities, accidents involving the release of hazardous chemical and radiation substances, domestic and man-made fires, and accidents in life support systems).

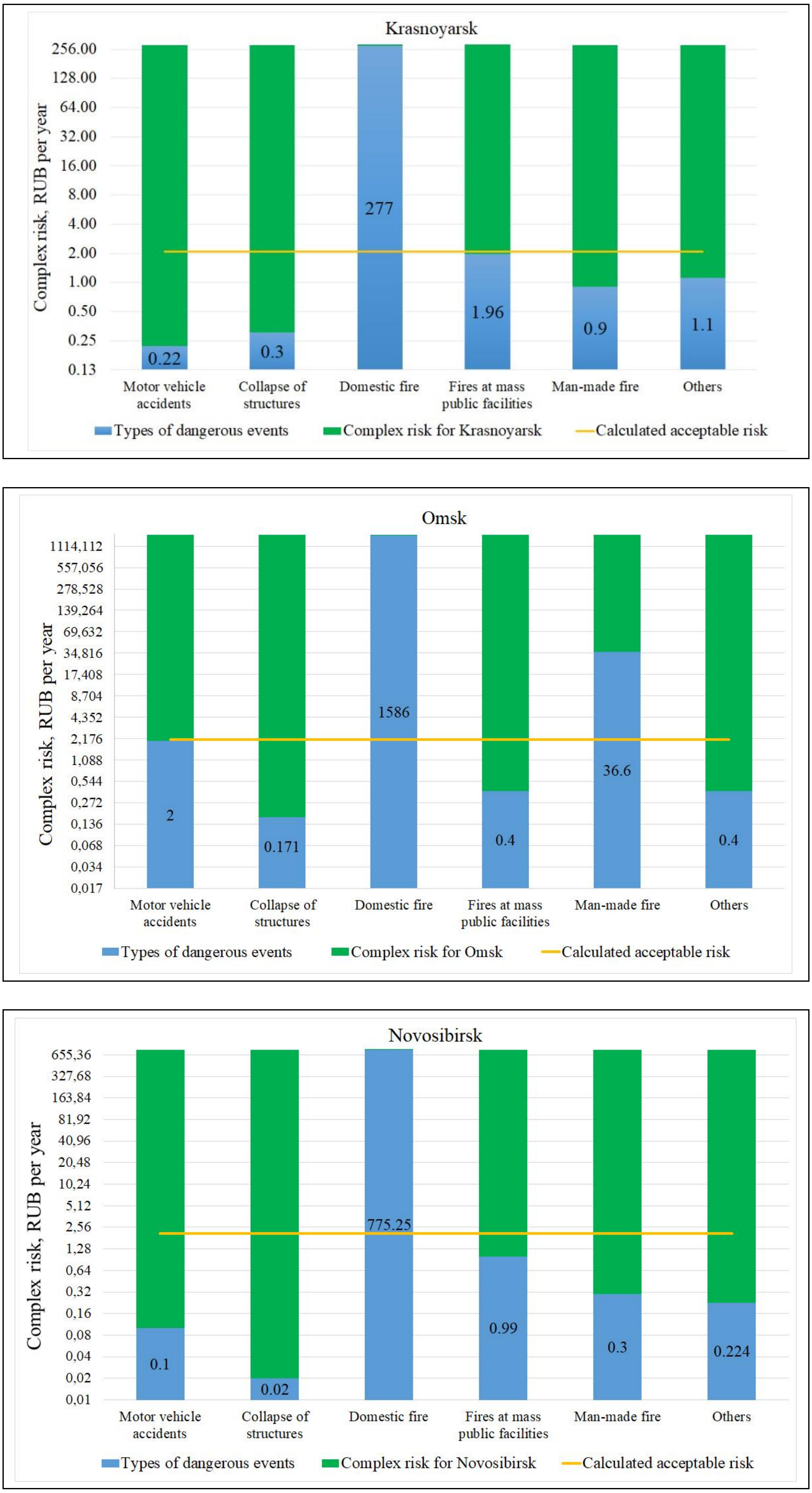

Fig. 2. The distribution of complex technogenic territorial risk values by type of hazards: three industrial agglomerations of Siberia.

For the three agglomerations, the dominant types of dangerous events were determined by solving the inverse problems. For Krasnoyarsk and Novosibirsk, the main hazard is associated with domestic fires and fires at mass public facilities; for Omsk, domestic fires, fires at mass public facilities, and large motor vehicle accidents. The main problem inherent in all these agglomerations, to be minimized and managed, is domestic fires. Figure 3 shows the resulting graphs of the complex territorial technogenic risk when managing two indicators, the amount of damage and the number of fatal outcomes (formulas (4) and (5), respectively).

Reducing the value of one indicator (the number of fatal outcomes or the amount of damage) allows reducing the risk value. Therefore, the main recommendations to minimize the risk should be aimed at (a) improving the culture and overall level of safety (reducing the number of fatal outcomes) and (b) property insurance to compensate for damage in case of a dangerous man-made event. To achieve an acceptable risk level in the territories, the amount of damage or the number of fatal outcomes must be decreased by 8 times for Novosibirsk, 6 times for Krasnoyarsk, and 10 times for Omsk.

To maintain the necessary level of stability to adverse effects, we calculated the protection indicator by formulas (5)–(7) and analyzed the number of rescue units and medical facilities in the three agglomerations; see Table 3.

The lowest protection was revealed for Novosibirsk (a lack of fire and rescue units and medical facilities). Thus, to prevent accidents and disasters and minimize the consequences of the realized events, it is necessary to improve the protection of this territory by increasing the number of emergency rescue units and emergency services and upgrading them.

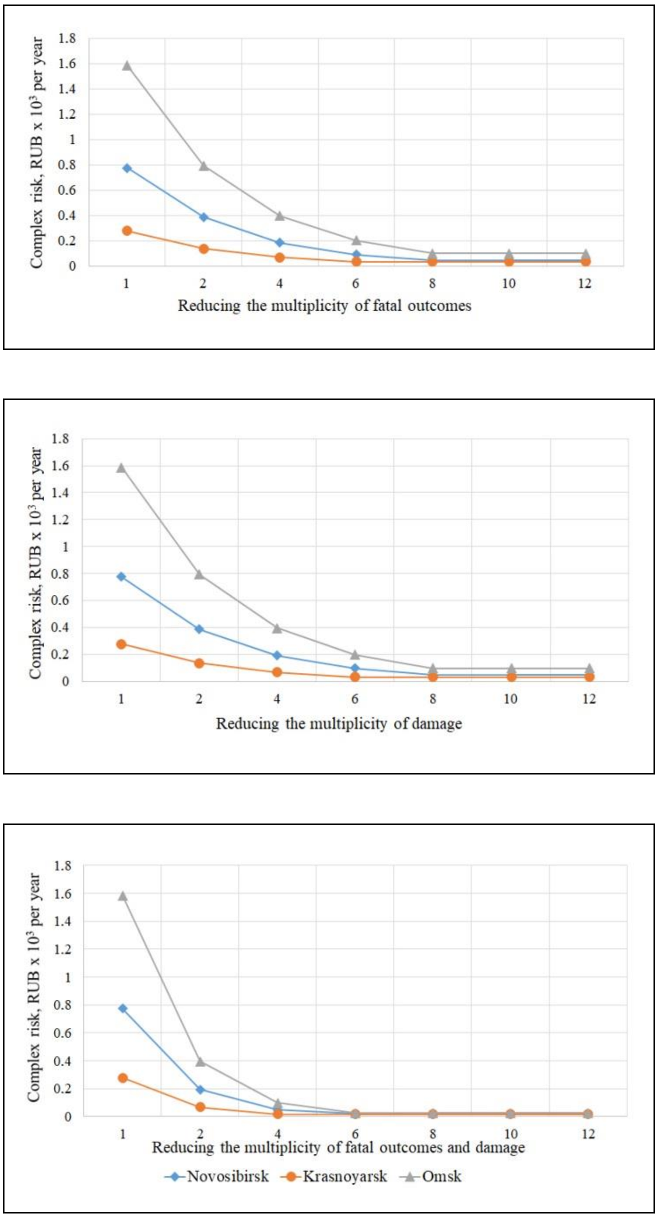

Fig. 3. Complex risk under decreasing multiplicity of fatal outcomes and damage.

Table 3

Values of the protection indicator and related data

Territory	Protection, %	The factual number of fire units	The normative number of fire units	The factual number of medical facilities	The normative number of medical facilities
Novosibirsk	84.5	25	30	68	80
Omsk	135	22	22	85	57
Krasnoyarsk	98.5	10	18	55	48

5. DISCUSSION

The main goal of territorial management is to achieve an acceptable risk level. However, regulatory and technical documents on the assessment of man-made territorial risk have several methodological problems and contradictions in their application due to the different legal statuses and inconsistency of norms. The key problem of the current regulatory and technical documents in the field of safety and risk assessment is that the acceptable risk levels are not scientifically sound. The mathematical framework of risk assessment requires refinement: besides emergencies, it is necessary to analyze all incidents occurring in a given territory that may cause major accidents and disasters in the future. The developed risk assessment methodology based on multidimensional statistical analysis allows reducing the acuteness of these problems and contradictions.

In Russia, the provision of territorial technogenic safety is entrusted to the territorial agencies for civil defense and emergency situations and the territorial departments of the Ministry of the Russian Federation for Civil Defence, Emergencies and Elimination of Consequences of Natural Disasters (Emercom). For effective management, it is reasonable to use information decision support systems, which should combine and analyze the monitoring data available to various agencies and assess risks in the main areas of life. Man-made risk management includes the development and implementation of activity programs to prevent dangerous events, reduce their possible consequences, perform monitoring, and improve the economic effectiveness of measures reducing risk values to acceptable levels. The information system of territorial risk and safety management serves to identify the main factors of high man-made risks and specify preventive measures.

Assessment of the efficiency and economic feasibility of managerial decisions to minimize risks is a separate practical task that requires basic information on different costs (the reconstruction of technical facilities, the development of facility monitoring systems, healthcare and safety systems, the creation and upgrading of emergency response and rescue units, etc.). The implementation of such measures is the responsibility of various federal ministries and departments of the Russian Federation, regional authorities, and enterprises.

CONCLUSIONS

In this paper, the complex technogenic territorial risk values have been calculated for three industrial agglomerations of the Siberian Federal District. Based on their analysis, the main causes affecting the risk level have been identified: man-made fires, accidents in the housing and communal service systems (heating networks, power grids, water supply systems, etc.), and motor vehicle accidents. The largest number of fatal outcomes is observed for domestic fires. The highest material damage is caused by man-made fires due to numerous victims and significant economic losses to eliminate the emergencies and their consequences.

Among the advantages of the developed risk assessment methodology, note the possibility of calculating an acceptable risk level, which can be used to elaborate regulatory documents. The current approaches to quantifying acceptable risk levels refer to individual risks, and qualitative indicators (rating points) are often adopted for normalizing the complex risk. In addition, the protection of a given territory is often assessed by qualitative methods. The methodology proposed in this paper yields numerical values of the protection indicator, for the first time in the literature.

The complex safety of territorial units should be assessed by developing and applying risk analysis criteria and methods. With the growing anthropogenic load, the use of technologies threatening the reproduction of natural resources, and numerous threats to the life and health of the population, there is an urgent need for effective territorial management mechanisms with decision support within the information system of territorial risk and safety management based on the comprehensive assessment of man-made territorial risks.

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